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**Adjustment and Validation of The Mathematical  
Prediction Model for Sweat Rate, Heart Rate,  
and Body Temperature Under Outdoor Conditions**



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<p>The Military Ergonomics Division at USARIEM has developed, based on their indoor laboratory studies, individual predictive equations for rectal temperature (<math>T_{re}</math>) and sweat loss (<math>m_{sw}</math>). These primary physiological inputs serve in a comprehensive model that predicts the expected physical work/rest cycle, the maximum single physical work time, and the associated water requirements. The present study was conducted in order to validate, and if necessary to adjust, these predictive equations and model for use under outdoor conditions with special reference to soldiers wearing CB protective garments. Three groups of</p>					
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19. Abstract (continued)

young male volunteers were exposed to three different climatic conditions (30°C, 65% rh; 31°C, 40% rh; 40°C, 20% rh). They were tested both in shaded and open field areas (radiation: 90 and 900 W·m<sup>-2</sup>, respectively), while at different work loads. Exercise consisted of two bouts of 10 min rest and 50 min walk on a treadmill, at a constant speed (1.4 m·s<sup>-1</sup>) and different grades. The subjects were tested wearing BDUs and protective garments in a MOPP 4 configuration. Their T<sub>re</sub>, HR and T<sub>sk</sub> were monitored every 10 min; VO<sub>2</sub> was measured towards the end of each bout of exercise; water loss was calculated for the entire 120 min exposure. We concluded that: a) the original model overestimated the actual physiological responses when applied outdoors; b) radiative and convective heat exchange should be considered separately when using the model outdoors, but can be used in their original form indoors; c) radiative heat exchange should consider short wave radiation (H<sub>r</sub>) and long wave emission from the body (H<sub>l</sub>) as follows:

$$H_r = 1.5 \cdot \Delta MRT / I_T; \text{ (watt)}$$

$$H_{lcorr} = \epsilon \cdot 0.053 \cdot \sigma / I_T; \text{ (watt)}$$

where:

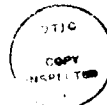
$\Delta MRT$  = solar heat transfer equation

$\epsilon$  = emissivity coefficient 0.9

$\sigma$  = Stephan-Boltzman coefficient.

$I_T$  = effective clothing insulation coefficient

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## INTRODUCTION

Over the last two decades, the Military Ergonomics Division at the US Army Research Institute of Environmental Medicine (USARIEM) has been establishing the data base and developing series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers doing physical work in various environmental extremes. Individual predictive equations for rectal temperature, heart rate and sweat loss as a function of the physical work intensity, environmental conditions and particular clothing ensemble were published (4,5,17). In addition, important modifying factors such as energy expenditure (8) and state of heat acclimation (6) have been evaluated and appropriate predictive equations developed. Suitable data bases to evaluate the predictive importance of cardiorespiratory physical fitness (9,15) gender (12,14,16) and state of hydration (12,13) have been established.

### Rectal Temperature Prediction

The general formula for predicting the final equilibrium rectal temperature ( $T_{re(f)}$ ) was suggested by Givoni and Goldman (4) as:

$$T_{re(f)} = 36.75 + 0.004(M - W_{ex}) + 0.0011 H_{(r+c)} + 0.8 \exp[0.0047(E_{req} - E_{max})] \quad ; \text{ } (^{\circ}\text{C}) \quad (1)$$

This equation is comprised of three components:

a) the metabolic component:  $[36.75 + 0.004 (M - W_{ex})]$

where M is the metabolic rate of walking or standing ( $M_w$ )  
as originally published by Pandolf et al. (9):

(2)

$$M_w = 1.5W + 2.0(W+L)(L/W)^2 + n(W+L)[1.5(V_w)^2 + 0.35GV]$$

or the metabolic rate of running ( $M_r$ ) as was recently  
suggested by Epstein et al (3) as:

(3)

$$M_r = M_w - 0.5(1 - 0.01L)(M_w - 15L - 850)$$

and:

(4)

$$W_{ex} = 0.098G(W+L)V_w$$

as suggested by Givoni and Goldman (4)

where:

M = metabolic rate ; (watt)

$M_w$  = metabolic rate of walking; (watt)

$W_{ex}$  = external work; (watt)

W = nude body weight; (kg)

L = clothing and equipment weight; (kg)

n = terrain factor

$V_w$  = walking velocity; ( $m \cdot s^{-1}$ )

G = grade; (%)

b) the dry heat exchange component:  $[0.0011 H_{(r+c)}]$

where:

(5)

$$H_{(r+c)} = 6.45 A_D (T_{db} - \bar{T}_{sk}) / I_T$$

as implied by Givoni and Goldman (4)

where:

$A_D$  = body surface area; ( $m^2$ )

$T_{db}$  = dry bulb temperature; ( $^{\circ}C$ )

$\bar{T}_{sk}$  = average skin temperature; ( $^{\circ}C$ )

$I_{T=clo}$  = total insulation including air layer ( $I_a$ )  
and intrinsic clothing; ( $I_{cl}$ )

c) the evaporative heat exchange component:

$$0.8 \exp [0.0047(E_{req} - E_{max})]$$

as shown by Givoni and Goldman (4)

where:

(6)

$$E_{req} = (M - W_{ex}) + H(R + C)$$

and:

(7)

$$E_{max} = 14.21 i_m / I_T A_{Deff} (P_{sk} - \phi_a P_a)$$

Where:

$i_m$  = permeability index (N.D.)

$A_{Deff}$  = effective surface area for evaporation; ( $m^2$ )

$P_{sk}$  = water vapor pressure at the skin; (mmHg)

$\phi_a$  = relative humidity; (%)

$P_a$  = saturated water vapor pressure of air at  $T_{db}$ ;  
(mmHg)

The validity of this prediction model was tested under different conditions. Figure 1 presents a comparison for 12 volunteer male subjects of the predicted (lines) and measured (points) time patterns for rectal temperature during one hour cycles of rest, physical work, and recovery as originally published by Givoni and Goldman (4). These findings suggest that the prediction of rectal temperature from the proposed

equations is in good agreement with the experimental observations covering a wide range of metabolic rates, climatic conditions and clothing properties. Figure 2 shows the comparison of predicted and observed rectal temperature responses for 12 soldiers while wearing three different military clothing ensembles during tests under two different climatic conditions. These data which were collected independently are in quite good agreement with the predicted values, and in all but two instances, the observed responses are within  $\pm 1$  S.D. of predicted (11).

#### Sweat Loss Prediction

The general equation for predicting sweat loss response ( $\dot{m}_{sw}$ ) as a function of exercise, environmental and clothing interactions, as proposed by Shapiro et al. (17) is:

$$\dot{m}_{sw} = 27.9 E_{req} (E_{max})^{-0.455} ; (g \cdot m^{-2} \cdot h^{-1}) \quad (8)$$

where:

$\dot{m}_{sw}$  = change in body weight due to sweat loss

This prediction equation was derived from over 250 experimental exposures to a wide range of climatic conditions (ambient temperature, 20-54°C and relative humidity, 10-90%) while wearing various clothing ensembles (light clothing and heavy clothing of high permeability or low permeability) at different metabolic rates (rest to moderate physical work). Therefore, this formula can be employed over a wide range of  $E_{req}$  (50-360,  $W \cdot m^{-2}$ ) and  $E_{max}$  (20-525,

$W \cdot m^{-2}$ ). In the present form, this formula is more applicable for predicting water requirements; however, it can also be presented in appropriate units ( $W \cdot m^{-2}$ ) for predicting the rate of sweat loss (17).

A comparison of predicted and measured  $\dot{m}_{sw}$  for 111 individual exposures involving 24 soldiers is illustrated in Figure 3. These experiments considered ambient temperatures ranging from 35-49<sup>0</sup>C, relative humidities from 20-75%, different clothing ensembles and both resting and exercise evaluations. A correlation coefficient between the predicted and measured sweat loss of  $r=0.94$  was observed over a wide range of sweating responses (17).

#### Heart Rate Prediction

The general formula for predicting the final equilibrium heart rate ( $HR(f)$ ) as proposed by Givoni and Goldman (5) for heat acclimated people is:

$$HR(f) = 65 + 0.35(I_{HR} - 25); (bts \cdot min^{-1})$$

$$\text{for } 25 < I_{HR} < 225 \quad (10)$$

$$HR(f) = 135 + 45[1 - e^{0.01[I_{HR} - 225]}]; (bts \cdot min^{-1})$$

$$\text{for } I_{HR} > 225$$

where: (11)

$$I_{HR} = 100(T_{re(f)} - 36.75) + 0.4 W_{ex}$$



The accuracy of this prediction model, though presented by Givoni and Goldman (5) to be excellent is to be reinvestigated. (this model is beyond the scope of this study and therefore will not be discussed in further details in the present report).

#### Applicability of the current set of models

A comprehensive heat stress model has been programmed by the Military Ergonomic Division in USARIEM on a Hewlett Packard 41 CV hand held calculator (11). The current model deals with the interaction of various multi-disciplinary factors such as: the theoretical physics of heat transfer, the biophysics of clothing, the physiology of metabolic heat production - distribution and elimination, and related meteorological considerations. The primary calculator inputs available to the user are the clothing worn, metabolic work rate, expected level of heat casualties, state of heat acclimation, ambient air temperature and relative humidity, wind speed and solar heat load. Through the associated changes from these inputs in deep body (rectal) temperature and sweat loss, the predicted outputs are the expected physical work - rest cycle, the maximum single physical work time if appropriate, and the associated water requirements.

Daily experience revealed some limitations in using the current comprehensive model under outdoor conditions. In fact, it has been shown by the Israel Defence Forces (unpublished data) that the models as published in the open

literature overestimate actual measurements outdoors.

The present study was conducted in order to re-evaluate the models for rectal temperature and sweat rate and adjust them for use under outdoor climatic conditions.

## Methods

### Subjects

Forty three fit male volunteers, whose physical characteristics are summarized in table 1 participated in the study. Prior to the experiments, each subject underwent a complete medical examination which included E.C.G. at rest; urine analysis and SMA-12 screening chemistry, and a complete medical history was obtained. Potential subjects with evidence of significant abnormalities were excluded from participation in the study. Subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate. All subjects signed a form of consent.

### Experimental design

The study was conducted during the summer (July - September) in 2 phases as follows:

Phase I: the study was conducted in parallel in a coastal region of Israel and a semi-arid region. During this phase the original prediction models applicability to outdoor conditions was tested, and modified accordingly. The prediction model for sweat rate was originally tested in the semi-arid region and then validated in the coastal region; the prediction model for rectal temperature was investigated in the coastal region and validated in the semi-arid region.

Table 1: Physical characteristics of the subjects (mean $\pm$ SD)

	Age	Weight	Height	A <sub>D</sub>	$\dot{V}O_{2\max}$
	(yr)	(kg)	(cm)	(m <sup>2</sup> )	(L $\cdot$ min <sup>-1</sup> )
Coast I	19 $\pm$ 2	68.8 $\pm$ 7.6	180 $\pm$ 5	1.86 $\pm$ 0.11	3.59 $\pm$ 0.36
Semi arid	26 $\pm$ 1	65.3 $\pm$ 9.5	173 $\pm$ 6	1.78 $\pm$ 0.14	3.51 $\pm$ 0.69
Coast II	19 $\pm$ 2	71.2 $\pm$ 10	179 $\pm$ 5	1.89 $\pm$ 0.15	3.57 $\pm$ 0.75
Desert	18 $\pm$ 1	66.6 $\pm$ 5.6	180 $\pm$ 3	1.84 $\pm$ 0.10	3.72 $\pm$ 0.46

Phase II: the modified prediction models for sweat rate and rectal temperature were re-tested in a coastal and desert regions of Israel. During this phase the models were refined and brought to their final form.

#### Protocol

a) acclimatization: All participants were inhabitants of the region where they were tested (coast, semi-arid, desert). Therefore, they were naturally acclimated to the particular region climate. Furthermore, prior to experimental exposure all subjects underwent a 5 day acclimatization process. During this procedure they walked for 100 min on a treadmill at a speed of  $1.4 \text{ m}\cdot\text{s}^{-1}$  and 5% grade while wearing cotton BDU. The last day of acclimatization in phase I was devoted to familiarization with the protective gear. Subject underwent the acclimatization procedure during this day wearing full CB protective gear (MOPP IV).

b) maximal oxygen uptake ( $\dot{V}\text{O}_{2\text{max}}$ ): To determine aerobic power, oxygen uptake at maximal exercise was analyzed by the computerized metabolic chart (MMC-Horizon; SensorMedic). A progressive treadmill running test was done at a constant speed of  $3.13 \text{ m}\cdot\text{s}^{-1}$  and stepwise grade increments of 2% every 2 minutes until exhaustion. Established criteria were used to determine oxygen uptake (18). During this test subjects wore T-shirts, shorts and tennis shoes. The test was

conducted in the laboratory, under comfortable thermal conditions (20°C, 50% rh).

c) Experimental protocol: Each subject in phase I was tested under the following 18 experimental combinations:

Metabolic rate: Rest ( $\approx 100$  watts)  
Moderate work ( $\approx 300$  watts)  
Heavy work ( $\approx 450$  watts)  
Solar radiation: Sun (maximal solar radiation,  $\approx 900 \text{ W}\cdot\text{m}^{-2}$ )  
Shade (minimal solar radiation,  $\approx 80 \text{ W}\cdot\text{m}^{-2}$ )  
Clothing: Shorts only (clo = 0.74, im/clo = 0.94)  
Cotton BDU (clo=0.99, im/clo = 0.75)  
CB protective overgarment (MOPP IV)  
(clo=1.64, im/clo = 0.43)

The combinations were assigned at random to the subjects. While at rest, the subjects were seated on a bench. The work consisted of walking on a treadmill at a speed of  $1.4 \text{ m}\cdot\text{s}^{-1}$  ( $5 \text{ km}\cdot\text{h}^{-1}$ ) with no grade at the moderate work load, and with 5% grade for heavy work load. Each exposure lasted 120 min consisting of two cycles of 10 min rest and 50 min exercise. The study was conducted outdoors under a shade (6x6x6 m) specially designed for the study resembling a solar load of  $80 \text{ W}\cdot\text{m}^{-2}$ , and in an open space resembling a solar load of  $900 \text{ W}\cdot\text{m}^{-2}$ . All experiments were conducted between 12:00 and 14:00.

## Measurement and calculations

### a) Physiological parameters

On each day, physiological data obtained were: heart rate (HR) from ECG chest electrodes (CM5 placement); rectal temperature ( $T_{re}$ ) from a thermistor probe (YSI 401) inserted 10 cm beyond the anal sphincter, and skin temperatures ( $\bar{T}_{sk}$ ) by skin thermistors (YSI 409) at 3 locations (chest, arm, leg). Weighted mean skin temperature ( $\bar{T}_{sk}$ ) was calculated according to Burton (2).

Heart rates were continuously radio-telemetered to an oscilloscope tachometer (Lifescope 6; Nihon Kohden) and were recorded every 5 min. Rectal and skin temperatures were recorded every 15 min from a tele-thermometer (TUC-46; Yellow Springs instruments).

To determine metabolic cost, oxygen consumption ( $VO_2$ ) was measured after 40 min of each bout of exercise. Expiratory gases were collected and analyzed by the automatic metabolic cart (MMC-Horizon, SensorMedics).

Nude body weight was measured on an electronic precision scale ( $\pm 10$  g), before and after exposure. Water intake and urine output were precisely measured. Sweat rate was calculated from weight differences adjusted for water intake and urine output.

b) Environmental variables

Dry bulb temperature (DBT) and wet bulb temperature (WBT) were measured at the study's location in the shaded area, using a psychrometer (Lambrecht). The accuracy of these parameters were cross-tested by measuring ambient temperature and relative humidity with an electronic sensor (Rotronic). A 6-inch-diameter blackened copper sphere (Casella) provided the globe temperature ( $T_g$ ). All those parameters were measured at about 2 m from ground level and recorded every 15 min. Solar radiation was measured every 5 min using a pyranometer (EPLAB). The black globe temperature and solar radiation were measured both in the shaded and open areas. Wind speed was measured with a hot wire anemometer (Sierra) every 15 min.

c) Calculations

The basis for modeling  $T_{re}$  and  $m_{sw}$  are the models published by the U.S. Army Research Institute of Environmental Medicine (11). These models are based on the required evaporative cooling ( $E_{req}$ ) and the maximum evaporative capacity from the skin through the clothing and trapped air layers to the environment ( $E_{max}$ ) (models no. 6,7).

Mean radiant temperature (MRT) was also calculated according to the model used in USARIEM as follows:

$$\Delta MRT = (1 + 2.2 V_a^{0.5}) (T_g - T_a) ; (^{\circ}C)$$



## Results

Table 2 summarizes the environmental conditions under which the study was carried out. The average ambient temperature was slightly higher in the semi-desert area than in the coastal area, but was 8 to 9 °C higher in the desert area than in both coastal and semi-desert areas. The coastal area was humid ( $63.7 \pm 6.0\%$  rh); the semi-desert area was relatively dry ( $41.9 \pm 6.6\%$  rh) and the desert area was very dry ( $20.6 \pm 0.5\%$  rh). These were equivalent to ambient vapor pressure of  $20.6 \pm 2.8$ ,  $13.8 \pm 1.6$ , and  $10.7 \pm 0.4$  mmHg, respectively. Solar radiation was  $900 \pm 60$  W·m<sup>-2</sup> in open space and  $80 \pm 13$  W·m<sup>-2</sup> in the shade with not much difference between the three testing areas.

The average metabolic rates of the various exercise levels were:  $116 \pm 12$  watt at rest,  $344 \pm 30$  and  $469 \pm 46$  watt at the moderate and heavy work loads, respectively. No significant differences were found between the two bouts of exercise.

Minor changes ( $<0.2^\circ\text{C}$ ) were recorded in  $T_{re}$  at rest, while wearing BDU or protective garments. Differences in  $T_{re}$  response to exercise-heat stress were observed according to exercise intensity, solar load, and clothing.

The effect of moderate work load while wearing BDU was more pronounced in the coastal area than in the semi-desert

area (Fig 4); There was not much effect of solar load on  $T_{re}$  response, under these conditions (Fig 4,5) encapsulation in protective garments caused, under moderate work load, a significant increase in  $T_{re}$  which was more pronounced at the coastal area than the semi-desert area. Furthermore higher solar load caused  $T_{re}$  to increase more than in the shade (Fig 6,7).

Heavy work loads ( $500 \text{ W}\cdot\text{m}^{-2}$ ) caused a marked increase in  $T_{re}$  in all combinations tested. In the shaded area while wearing shorts,  $T_{re}$  increased more in the coastal area than in the semi-desert area (Fig 8) while exposure to the high solar load resulted in similar responses (Fig 9). Wearing BDU in the shade caused a similar pattern of change in  $T_{re}$  response in all 3 areas. However the response was higher in the coastal area than in the semi-desert area; the latter was higher than in the desert area (Fig 10). Similar responses of  $T_{re}$  were found, while exposed to high solar load, in the semi-desert and desert areas which were significantly lower than in the coastal area (Fig 11). Wearing protective garments was unbearable for our test subjects in the coastal area while tested under high solar load (Fig 12).

Sweat rates in the semi-desert area were lower from those recorded at the desert and the coastal areas (Fig 13-15). At moderate work the lowest value recorded was while wearing cotton BDU in the shade ( $406 \pm 79 \text{ g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) and the highest value was measured at the coastal area wearing MOPP IV in the sun ( $1012 \pm 140 \text{ g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) (Fig 14). At a

heavy work load, as presented in figure 15, the higher values were measured while wearing MOPP IV. There was no significant difference between the sweat rate measured in the desert and the coastal area. The higher value recorded were at the semi-desert area while wearing MOPP IV in the sun ( $1490 \pm 169$   $\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ ) an exposure that was unbearable in the coastal area.

The actual measured sweat rates and  $T_{re}$  were compared to those calculated according to the mathematical models to predict rectal temperature suggested by Givoni et al. and the mathematical model to predict sweat rate suggested by Shapiro et al. The comparison depicted in Figs 16,17 show that the predicted values are overestimating the actual results.

Table 2: Mean $\pm$ SD of climatic conditions during the study period at the different locations.

	Coastal	Semi Desert	Desert
$T_a$ ( $^{\circ}\text{C}$ )	30.2 $\pm$ 1.1	30.8 $\pm$ 1.5	38.8 $\pm$ 0.5
$T_w$ ( $^{\circ}\text{C}$ )	24.9 $\pm$ 1.5	21.5 $\pm$ 0.9	
$\Phi_a$ (%)	63.7 $\pm$ 6.0	41.9 $\pm$ 6.6	20.6 $\pm$ 0.5
$P_a$ (mmHg)	20.6 $\pm$ 2.8	13.8 $\pm$ 1.6	10.7 $\pm$ 0.4
S.R. sun ( $\text{W}\cdot\text{m}^{-2}$ )	893 $\pm$ 61	966 $\pm$ 68	945 $\pm$ 10
S.R. shade ( $\text{W}\cdot\text{m}^{-2}$ )	88 $\pm$ 13	79 $\pm$ 14	80 $\pm$ 4
$T_g$ sun ( $^{\circ}\text{C}$ )	48.4 $\pm$ 1.4	47.2 $\pm$ 1.8	53.3 $\pm$ 1.5
$T_g$ shade ( $^{\circ}\text{C}$ )	34.9 $\pm$ 1.1	35.1 $\pm$ 1.3	43.7 $\pm$ 1.1
$V_a$ ( $\text{m}\cdot\text{sec}^{-1}$ )	1.0 $\pm$ 0.3	1.5 $\pm$ 0.3	1.3 $\pm$ 0.3

Data analysis and development of the  
corrected model

Analysis of the 288 exposures from the first series of experiments yielded the predicted values for rectal temperature calculated according to Givoni and Goldman and the values for sweat rate predicted according to Shapiro et al. which overestimated the actual measured values (Fig. 16,17). By analyzing the components of the heat balance equation, upon which all prediction models are based, it was hypothesized that the radiative and the convective heat transfer were the "soft points". This emerges from the fact that the original models were developed at laboratory conditions under which environmental conditions could not be fully simulated. In 1979, Pandolf et al. investigated the influence of solar radiation on working subjects exposed to a heat load (10). They concluded that solar radiation should be considered as a component in predicting physiological parameters outdoors; however, they did not suggest any alternative correction factor.

Accordingly, during the first phase of the present study the radiative and the convective heat transfer were considered separately as follows:

(12)

$$T_{\text{ref}} = 36.75 + 0.004(M - W_{\text{ex}}) + 0.0011H_c + 0.0025H_r + 0.8 \exp[0.0047(E_{\text{req}} - E_{\text{max}})] ; \text{ } (^{\circ}\text{C})$$

The convective heat transfer ( $H_c$ ) was not modified from that proposed by Givoni and Goldman (eq. 5).

The radiative heat transfer ( $H_r$ ) based on solar radiation was calculated as follows:

(13)

$$H_r = K_0 \cdot A_D \cdot \Delta \text{MRT} / I_T ; \text{ (watt)}$$

Where:

$K_0$  = a physical constant found to be 1.5

$\Delta \text{MRT}$  = Mean radiant temperature as suggested by Bedford (1) and modified by USARIEM (See p. 14).

It emerges from eq. 12 that radiative heat contributes more than twice that of convection to the overall heat transfer. However, this model (eq. 12) was not found to be satisfactory (fig.18) and still overestimates the actual conditons.

The fact that the predictive model (eq. 12) deviated by a constant factor from the actual data, points to the fact that a component which relates to outdoor conditions should be considered. This component should express a fraction of heat dissipation by long wave emission from the body to the surrounding area ( $H_1$ ). This component is meaningfull only

outdoors because of the large gradient between skin temperature and the atmospheric temperature. Indoors, this temperature gradient is negligible which makes this component meaningless.

The long wave emission ( $W_b$ ) of a black body is defined by the Stephan Boltzman formula as follows (7):

(14)

$$W_b = \sigma \cdot T^4$$

where:

$\sigma$  = Stephan Boltzman constant,  $5.67 \cdot 10^{-8}$  ; ( $W \cdot m^{-2} K^{-4}$ )

$T$  = Body skin temperature (308 °K)

The formula shows that the total emissive power of a black body is proportional to the fourth power of its absolute temperature. However, when the Stephan Boltzman formula is applied to calculate the emissive power from a human body it should be modified. The human body is not a "black body" and is usually considered as a "grey body". Thus, the long wave emission from the human body to the atmosphere ( $H_{corr}$ ) is only 90% that of a black body as follows:

(15)

$$H_{lcorr} = 0.9 A_D \cdot W_b \cdot K_1 / I_T ; (\text{watt})$$

$K_1$  is a physical constant found to equal 0.053

Black globe temperature, was found to be slightly higher than ambient temperature ( $T_a$ ), when measured outdoors in a

shaded area;  $T_g$  equaled  $T_a$  under indoor studies. This indicate that  $T_g$  and  $\Delta MRT$  do not inherent long wave balance and thus should be corrected by  $H_l$ .

The corrected model to predict rectal temperature outdoors will therefore be as follows:

(16)

$$T_{re(f)} = 36.75 + 0.004(M - W_{ex}) + 0.0011H_c + 0.0025(H_r) - 0.021(H_{lcorr}) + 0.8 \exp[0.0047(E_{req}^* - E_{max})]; (^\circ C)$$

The long wave emission from the body to the atmosphere and the solar radiation were integrated also in  $E_{req}$  as follows:

(17)

$$E_{req}^* = (M - W_{ex}) + H_c + H_r - H_{lcorr}; (watt)$$

Three hundred and eighteen exposures were used to test the validity and applicability of the model (eq. 16) and the ability of the model to predict accurately rectal temperature. This is summarized in Fig. 19.

The mathematical model to predict sweat loss suggested by Shapiro et al. (model 8) was based on indoor laboratory studies and was found to overestimate when data were compared to sweat losses recorded in this study under outdoor natural climate (Figure 17). Based on the same principles as for  $T_{re}$ , the radiative heat transfer was considered separately



from the convective heat transfer. The evaporative heat loss was then corrected accordingly. Thus, the sweat rate model was adjusted as follows:

$$E_{req}^* = M + H_c + H_r - H_{lcorr}; \text{ (watt)} \quad (18)$$

where the convective heat transfer ( $H_c$ ) as proposed by Givoni (eq. 5), the radiative heat transfer based on solar radiation ( $H_r$ ) as calculated in eq. 13, and the long wave emission from the body to the atmosphere ( $H_{lcorr}$ ) as calculated in eq. 15.

The correct model was tested in this set of experiments and the ability to predict sweat rate was proved (Figure 20).

### Discussion

The ability to predict rectal temperature responses and sweat rate during exposure to different climatic conditions have been established (4,11,17). Numerous studies, conducted under controlled laboratory conditions, have validated the accuracy of the models used. Nevertheless, daily experience revealed that the prediction models, when applied in the field, are overestimating actual responses. By analyzing the different components of the models, it was hypothesized that dry heat exchange (R+C) should be considered differently indoors than outdoors. Indoors, when the surrounding is at a thermal equilibrium with the body, convection and radiation can be considered as one term according to Givoni and Goldman (4). However, when the models are applied outdoors, convection and radiation should be considered separately.

Analyzing the radiation component in the models it was established, in the present study, that two fractions of radiation should be considered: a) short wave radiation, through which heat is absorbed from the sun, and b) long wave radiation, through which heat is emitted from the body to the surrounding. Heat is emitted from the body by long wave radiation proportionally to the fourth power of temperature gradient between the skin and the atmosphere. Therefore, this factor becomes meaningful outdoors, where the gradient is high; but is meaningless indoors when the skin to ambient temperature gradient is negligible.

In conclusion, the original prediction models as suggested and established by USARIEM are valid under indoor conditions. When applied outdoors, dry heat exchange should consider not only short wave absorbance, but also long wave emission. The present study assimilated these components in the original models suggested by USARIEM.

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Fig 1: Comparison between measured (points) and predicted (lines) time patterns for rectal temperature under different climatic conditions and clothing ensembles (Ref: Givoni B., Goldman R.F; J. Appl Physiol. 34:201-204, 1973)

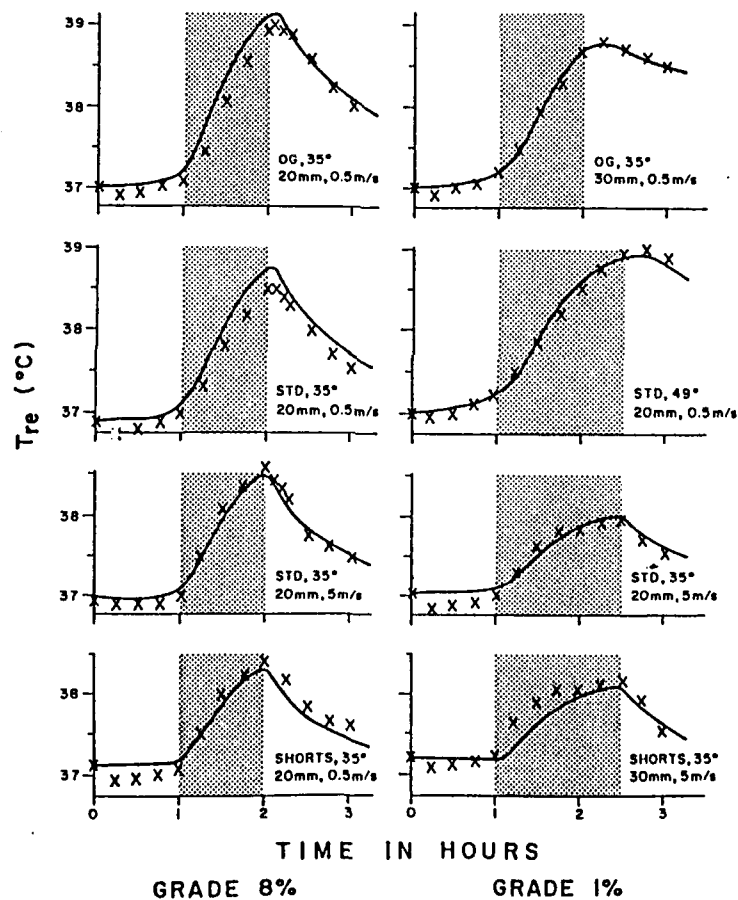


Fig 2: Comparison of predicted and observed rectal temperature responses while wearing different clothing ensembles under two different climatic conditions (Ref: Pandolf K.B. et al., Comp. Biol. Med. 16:310-329, 1986)

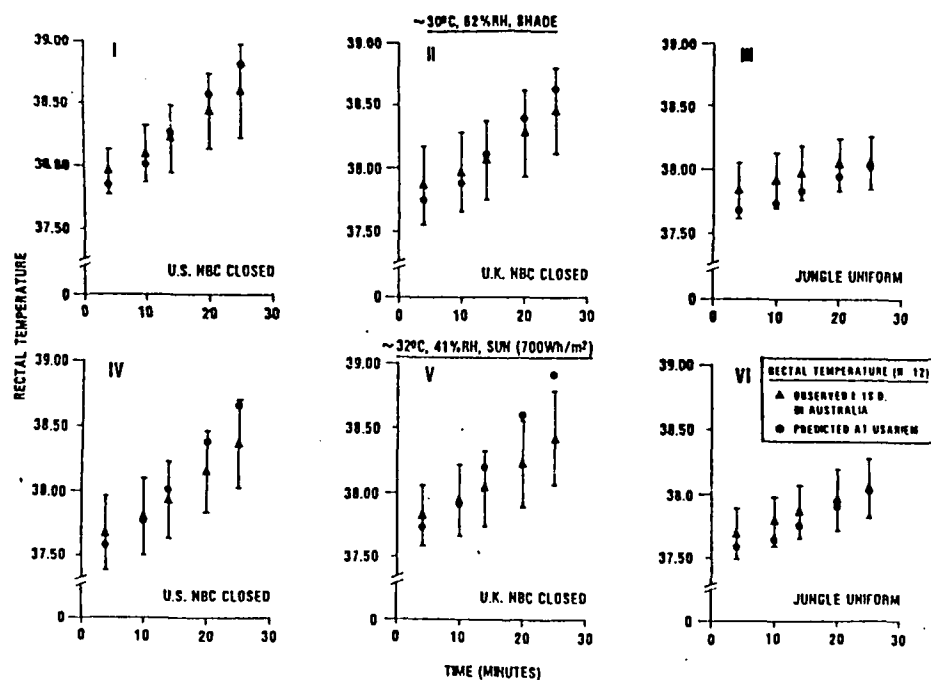
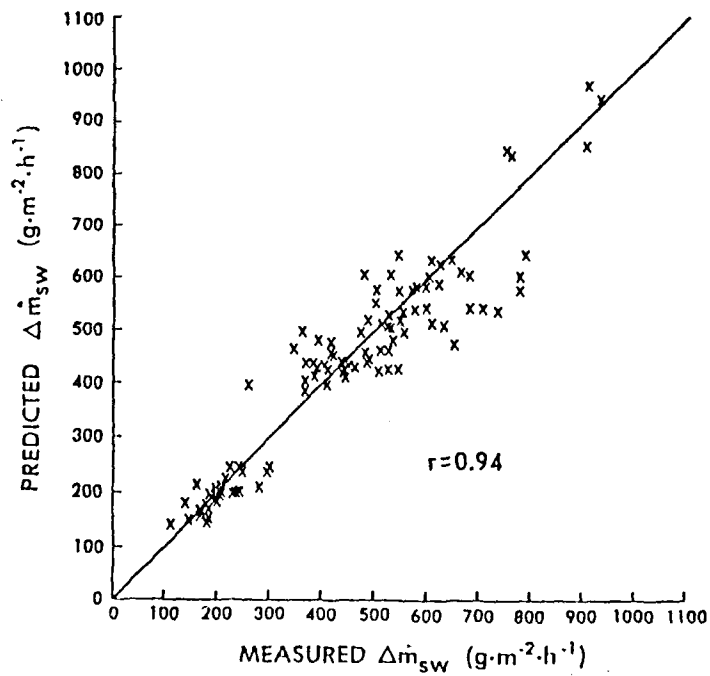




Fig 3: Comparison of predicted and measured sweat rates for III individual exposures. (Ref: Shapiro Y. et al.; Eur. J. Appl. Physiol. 48:83-96; 1982)



# Tre FATIGUES (shade) (moderate work load)

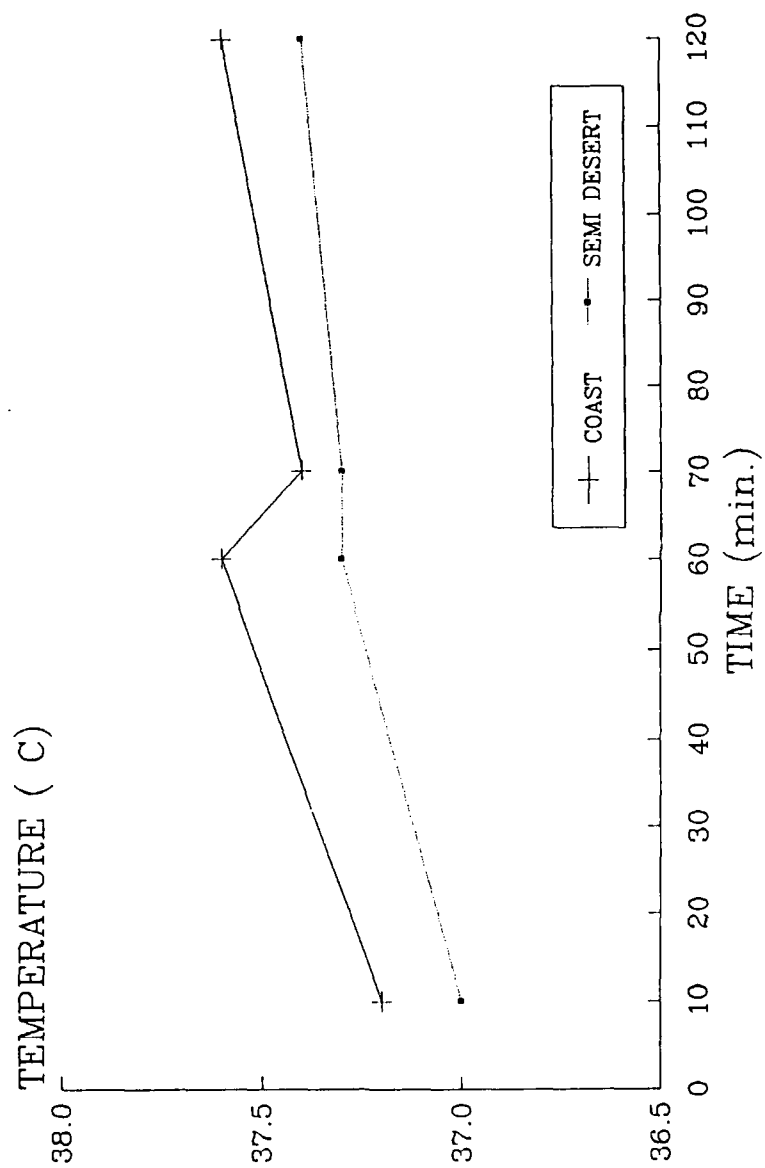


Fig. 4

Tre FATIGUES (sun)  
(moderate work load)

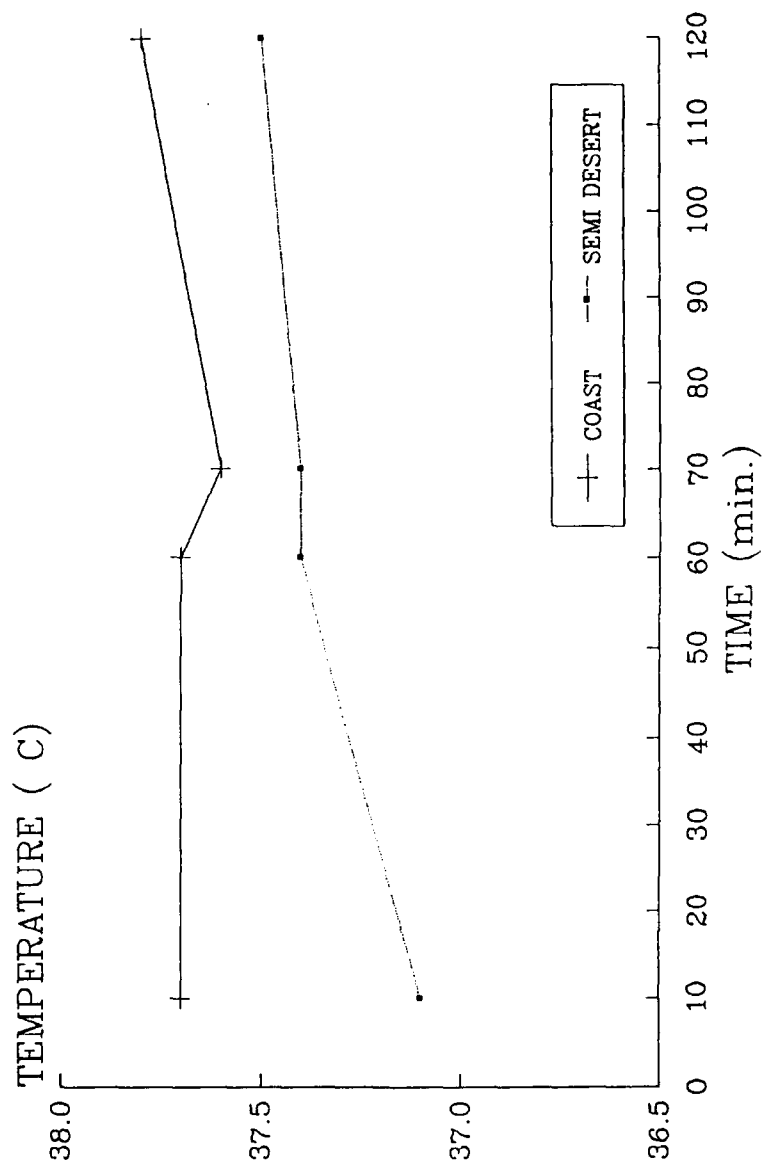


Fig. 5

Tre MOPP IV (shade)  
(moderate work load)

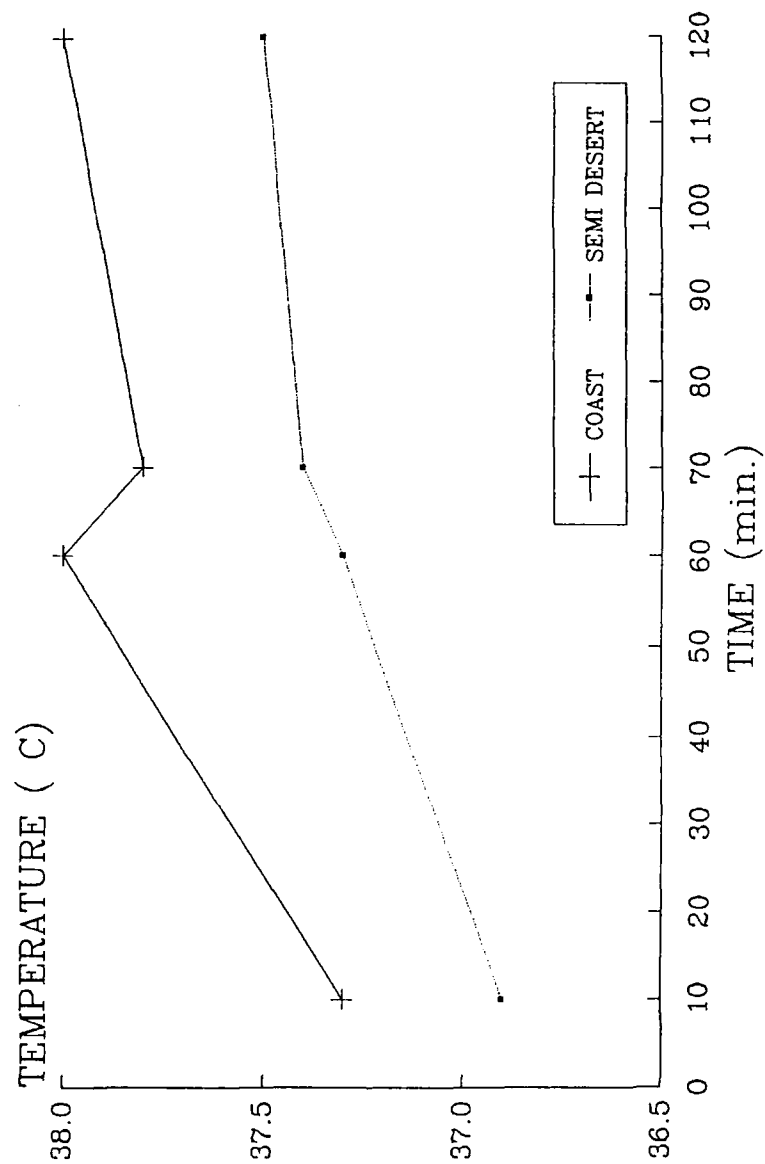


Fig. 6

Tre MOPP IV (sun)  
(moderate work load)

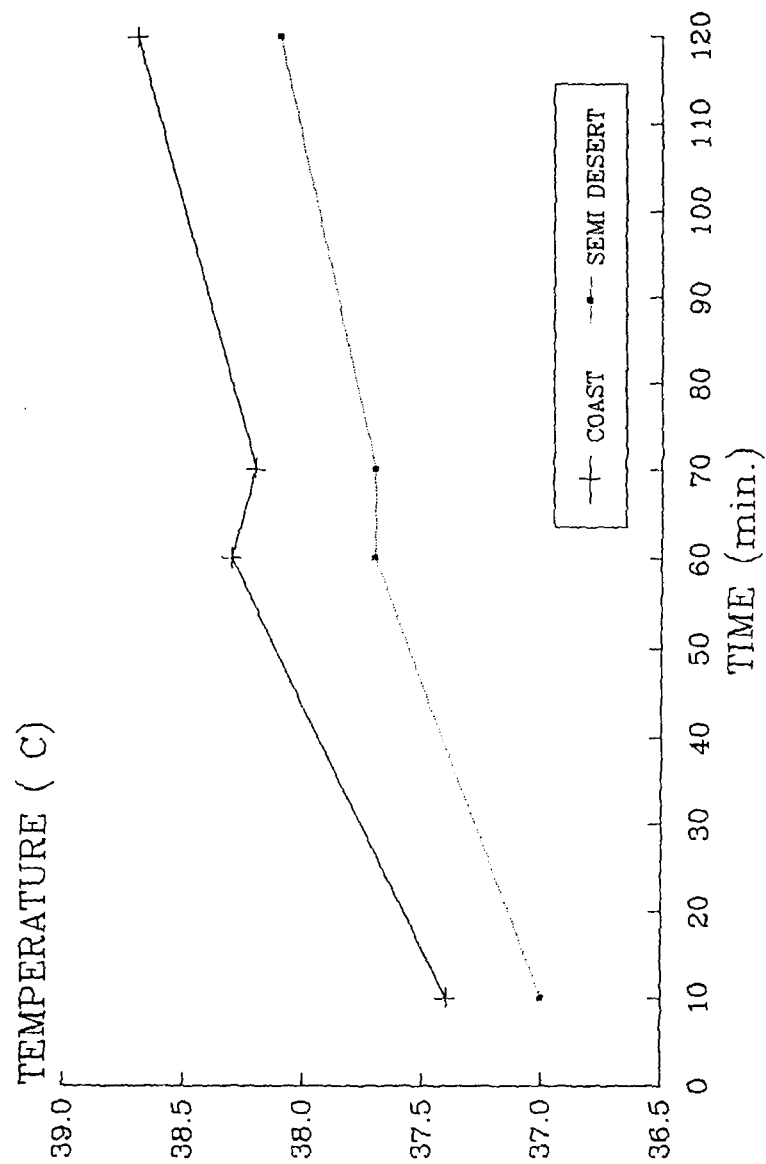


Fig. 7

# Tre SHORTS (shade) (heavy work load)

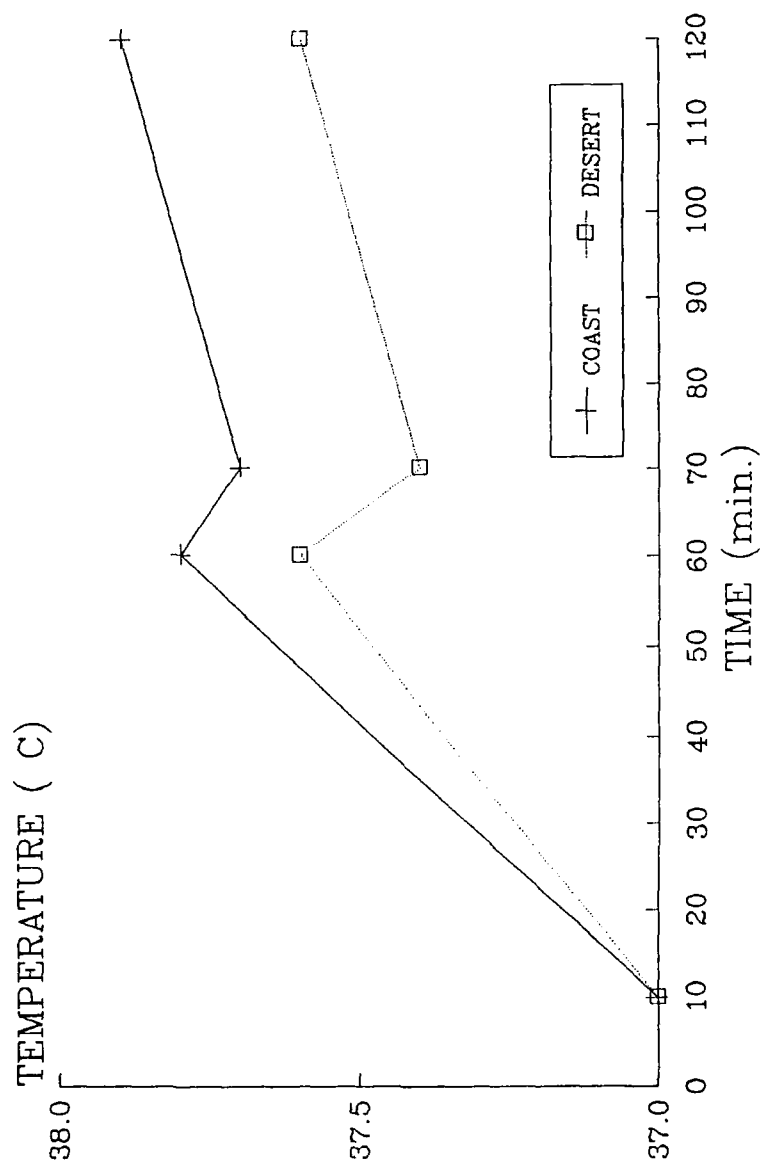


Fig. 8

# Tre -SHORTS SUN (heavy work load)

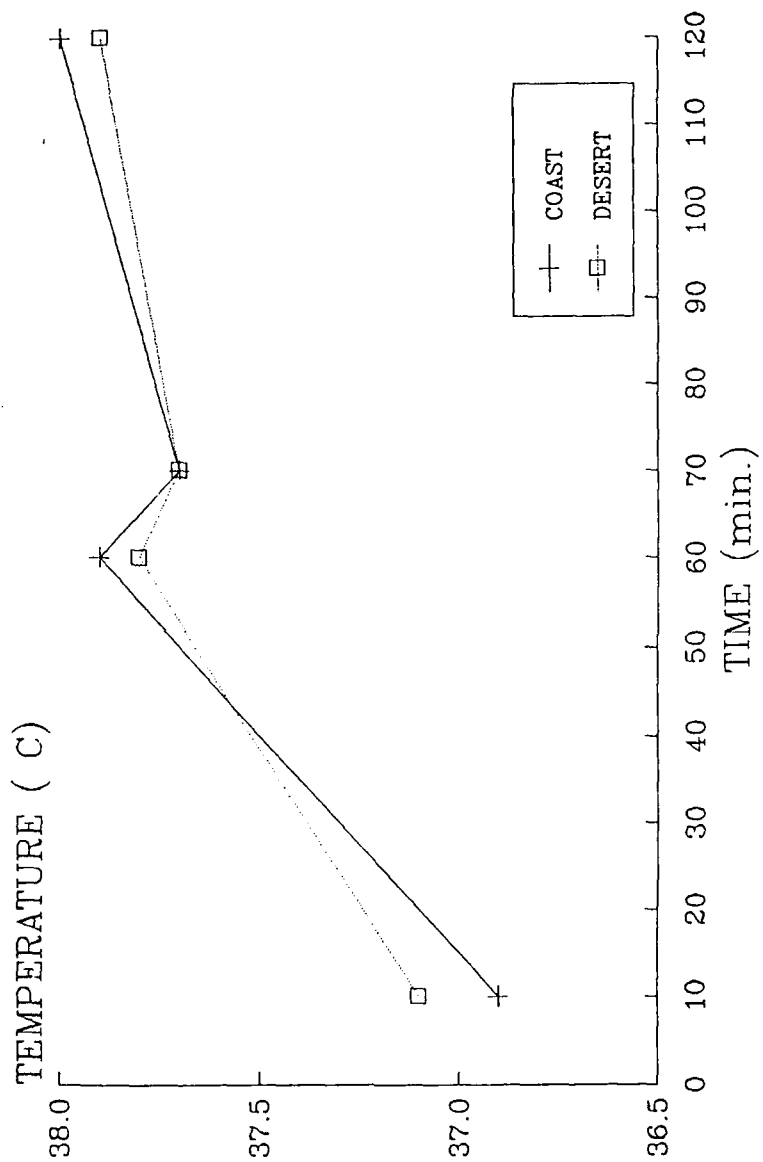


Fig. 9

# Tre FATIGUES (shade) (heavy work load)

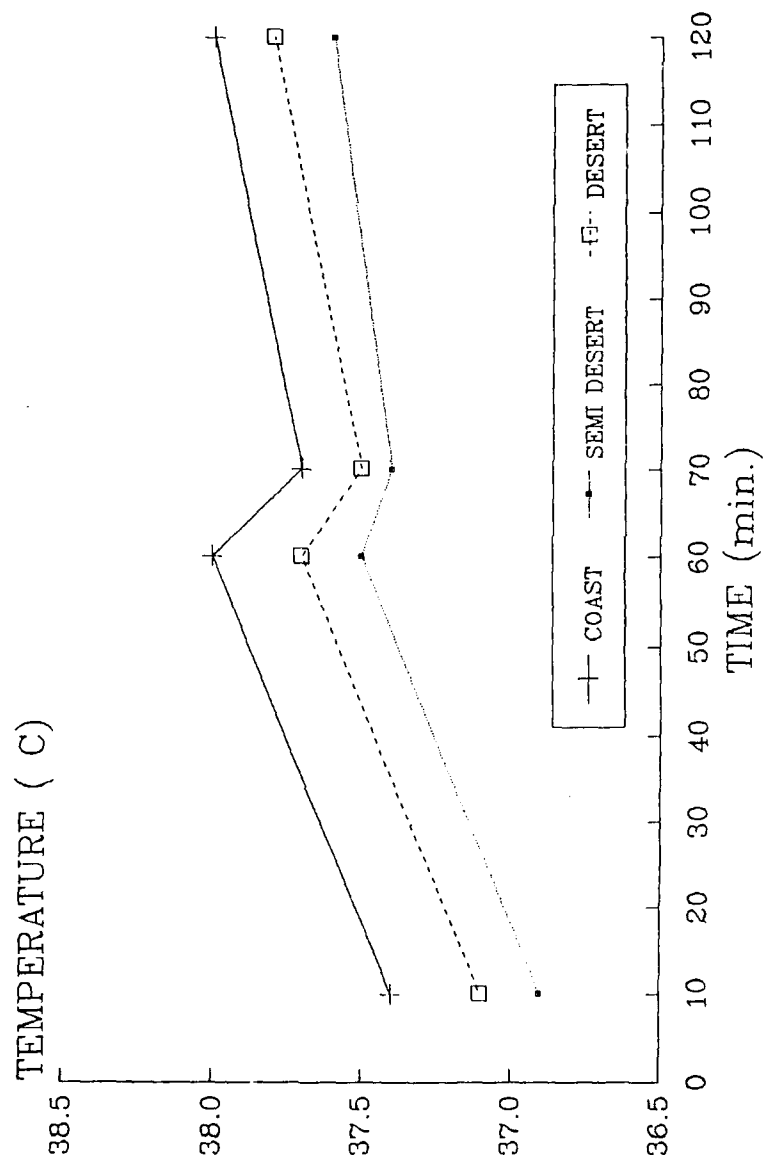


Fig. 10



# Tre FATIGUES (sun) (heavy work load)

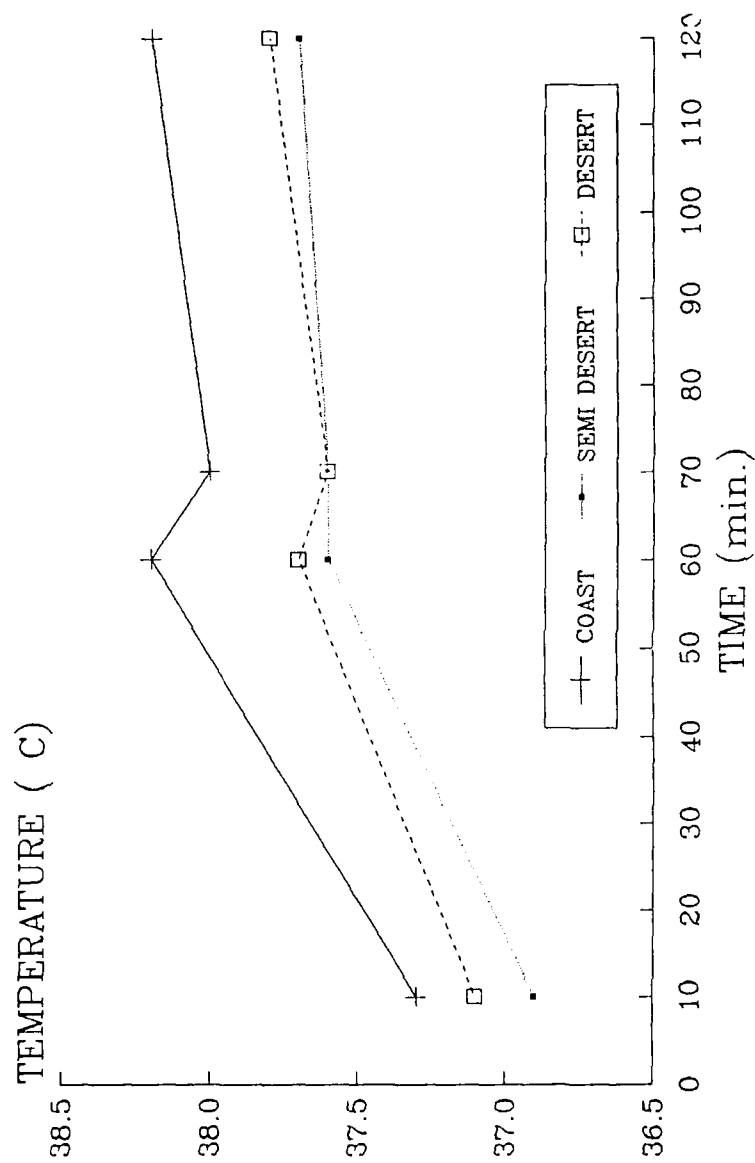


Fig. 11

Tre - MOPP IV  
(heavy work load)

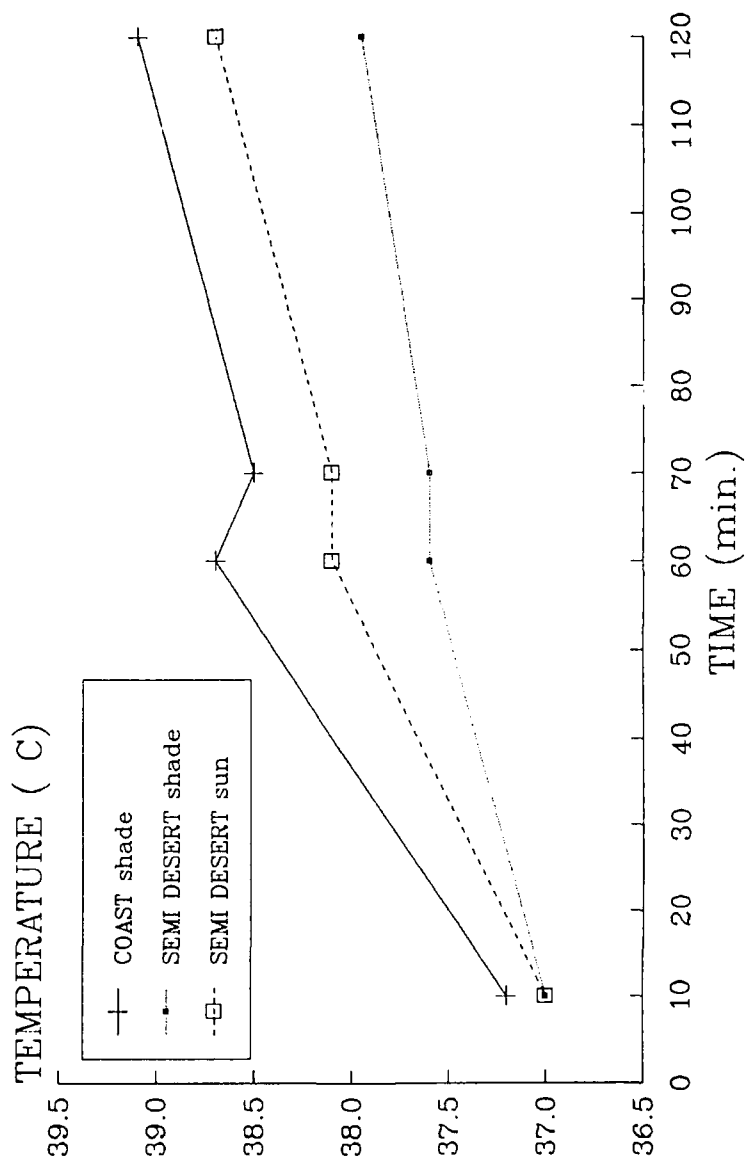


Fig. 12

# MEASURED SWEAT RATE REST

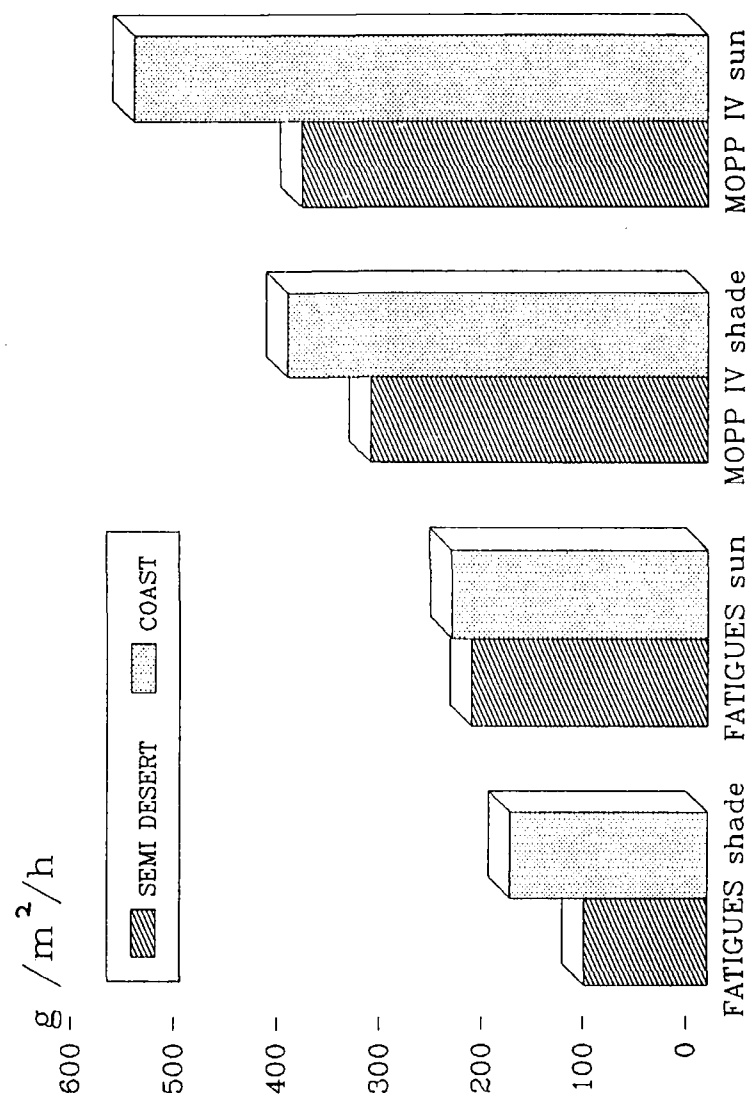


Fig. 13

# MEASURED SWEAT RATE MODERATE WORK

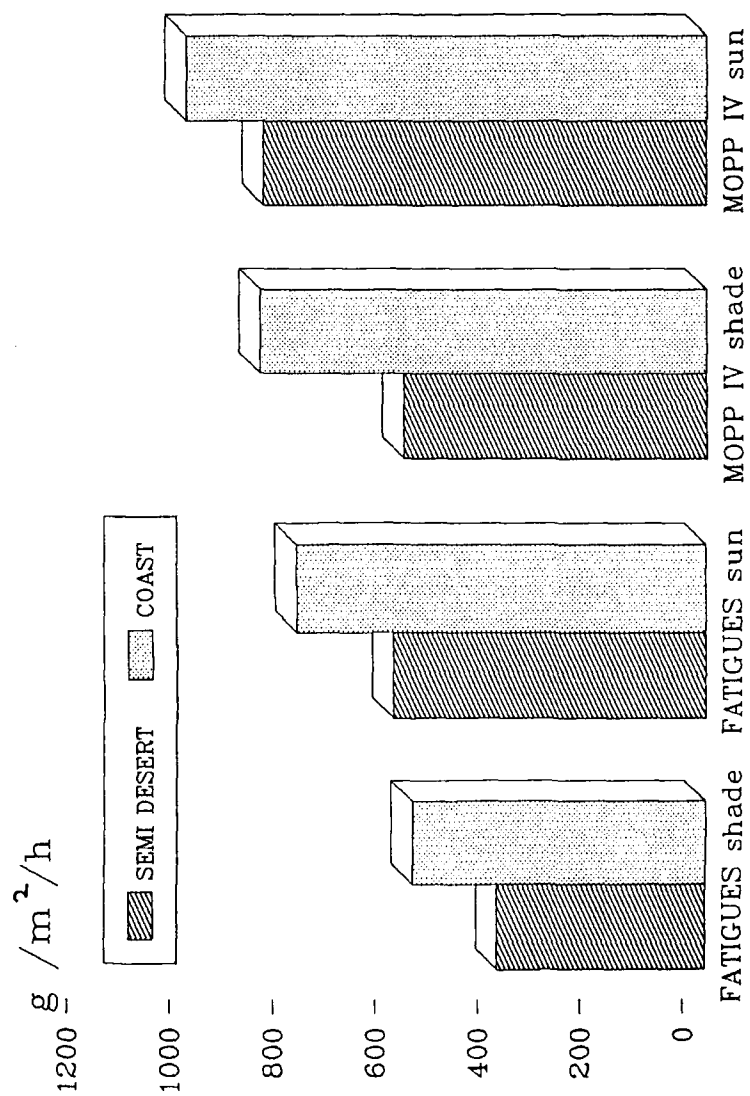


Fig. 14

# MEASURED SWEAT RATE HEAVY WORK

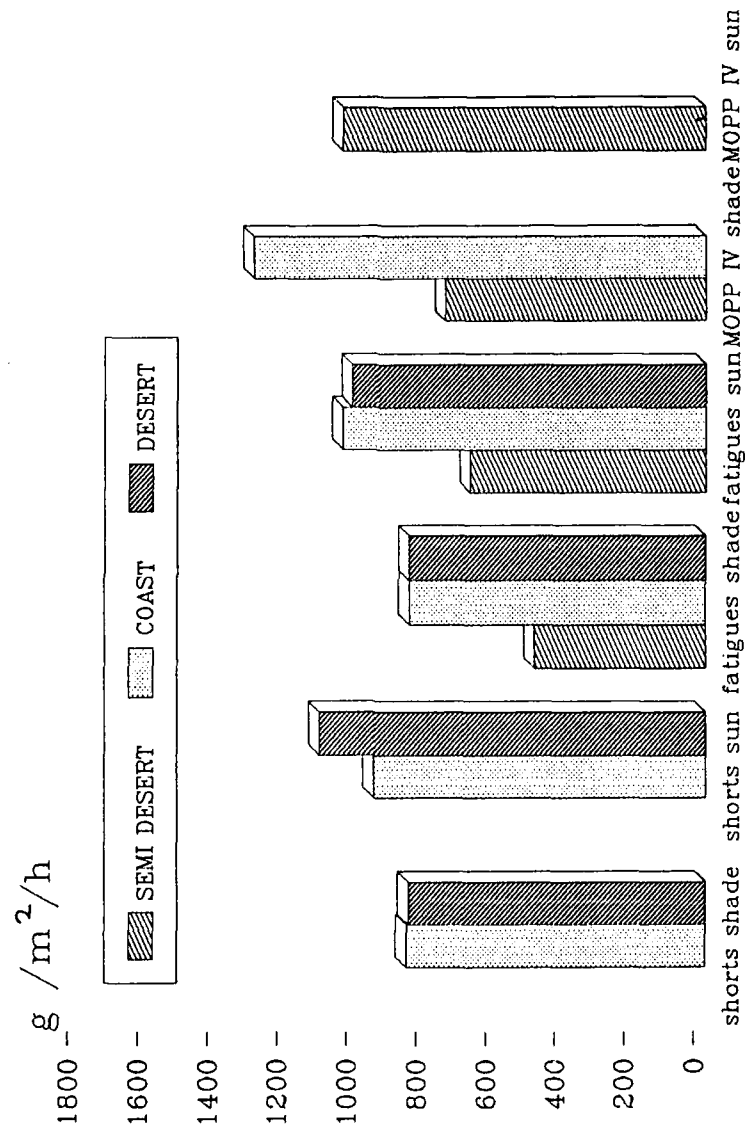


Fig. 15

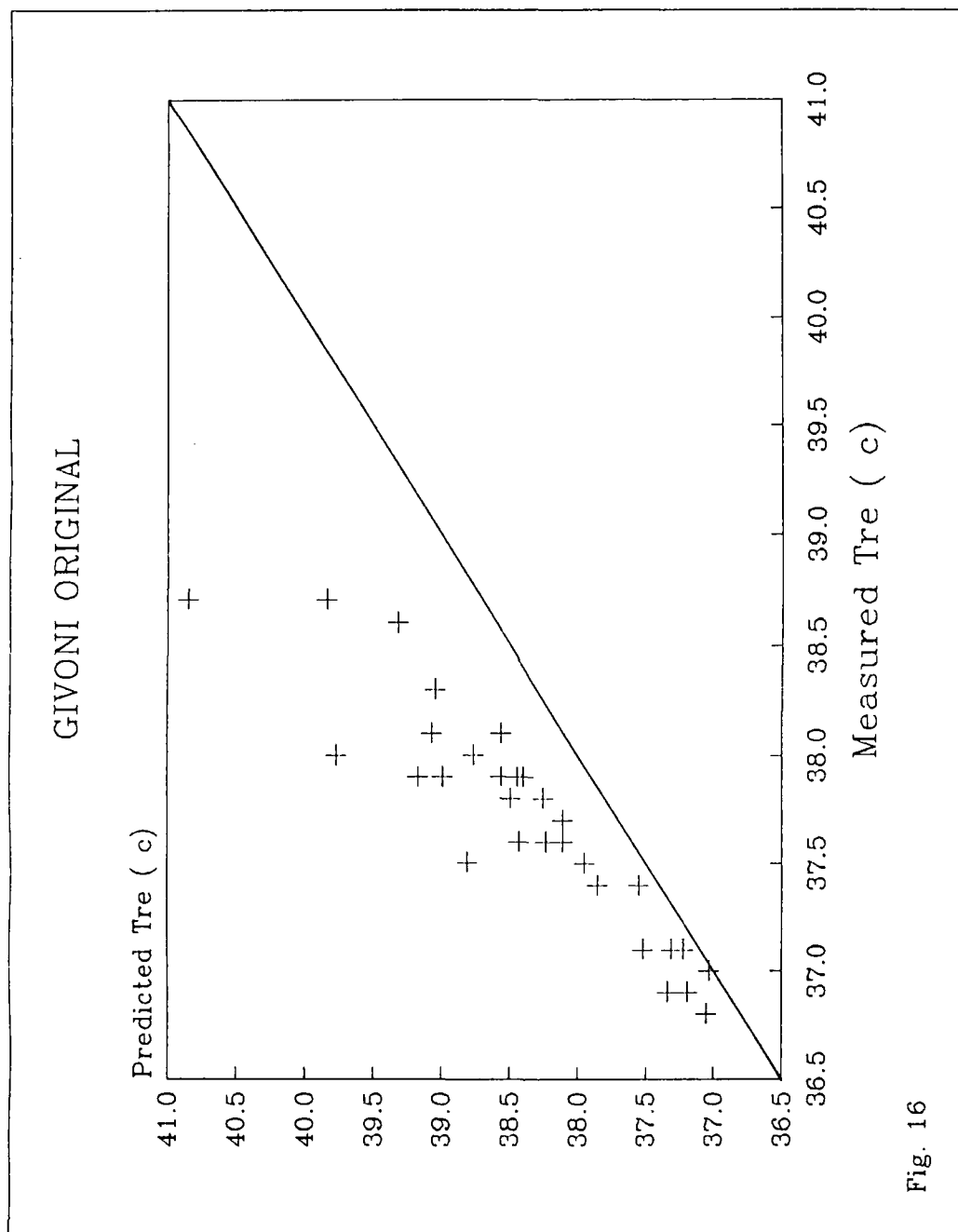


Fig. 16

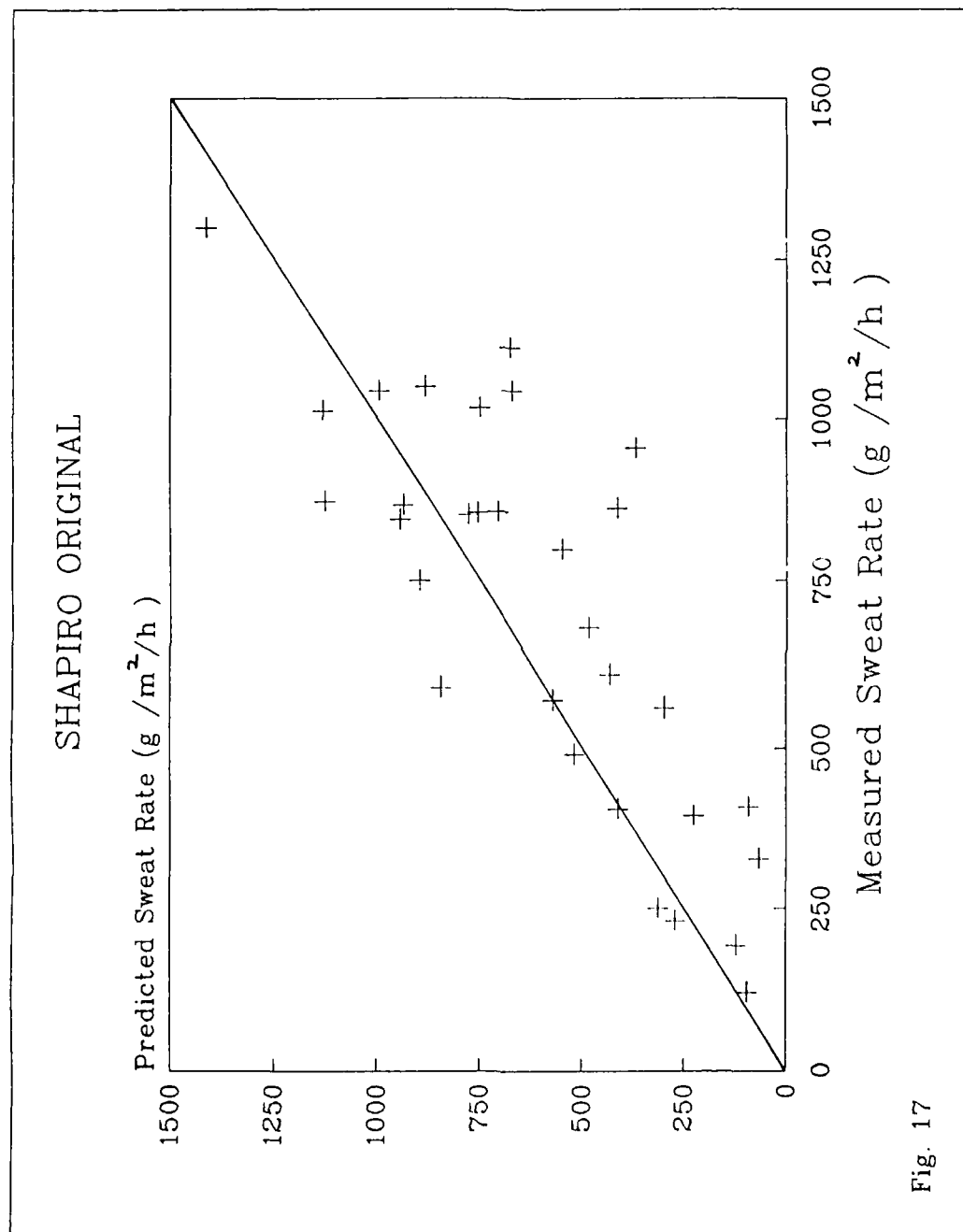


Fig. 17

# CORRECTED FOR Hr

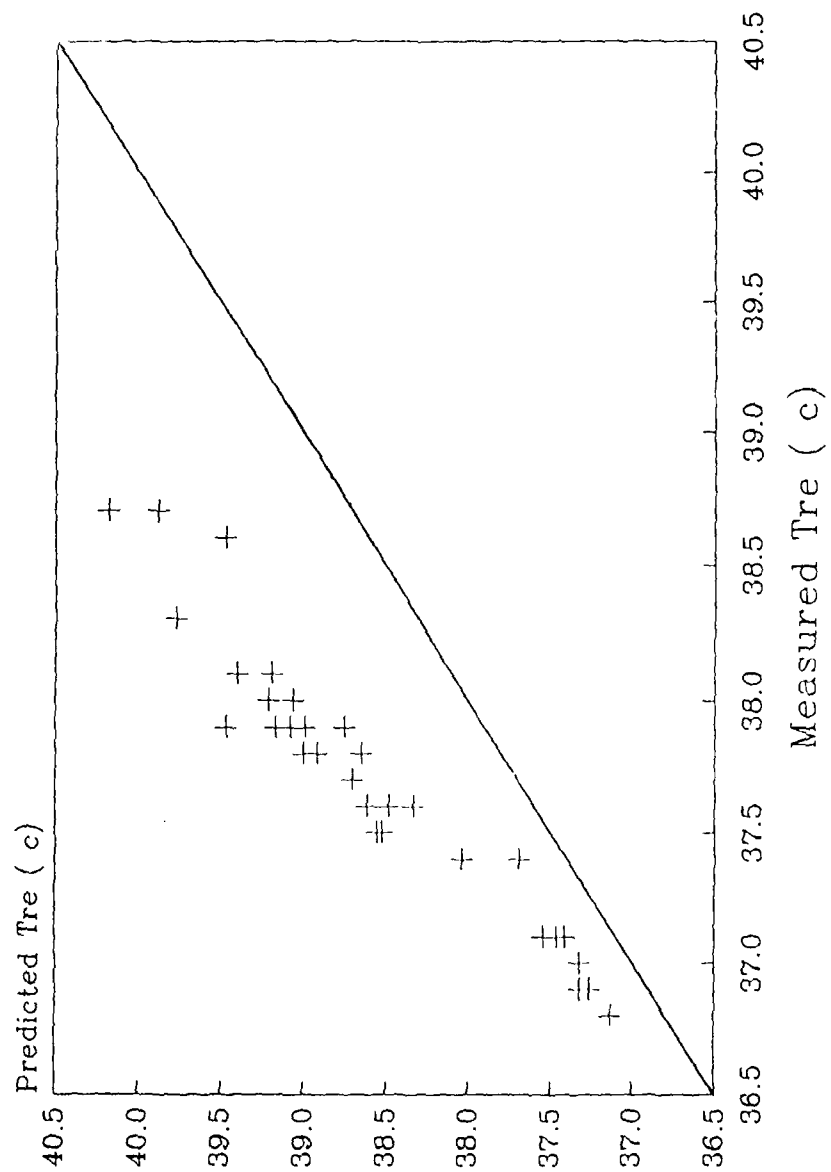


Fig. 18



CORRECTED FOR Hr & HI

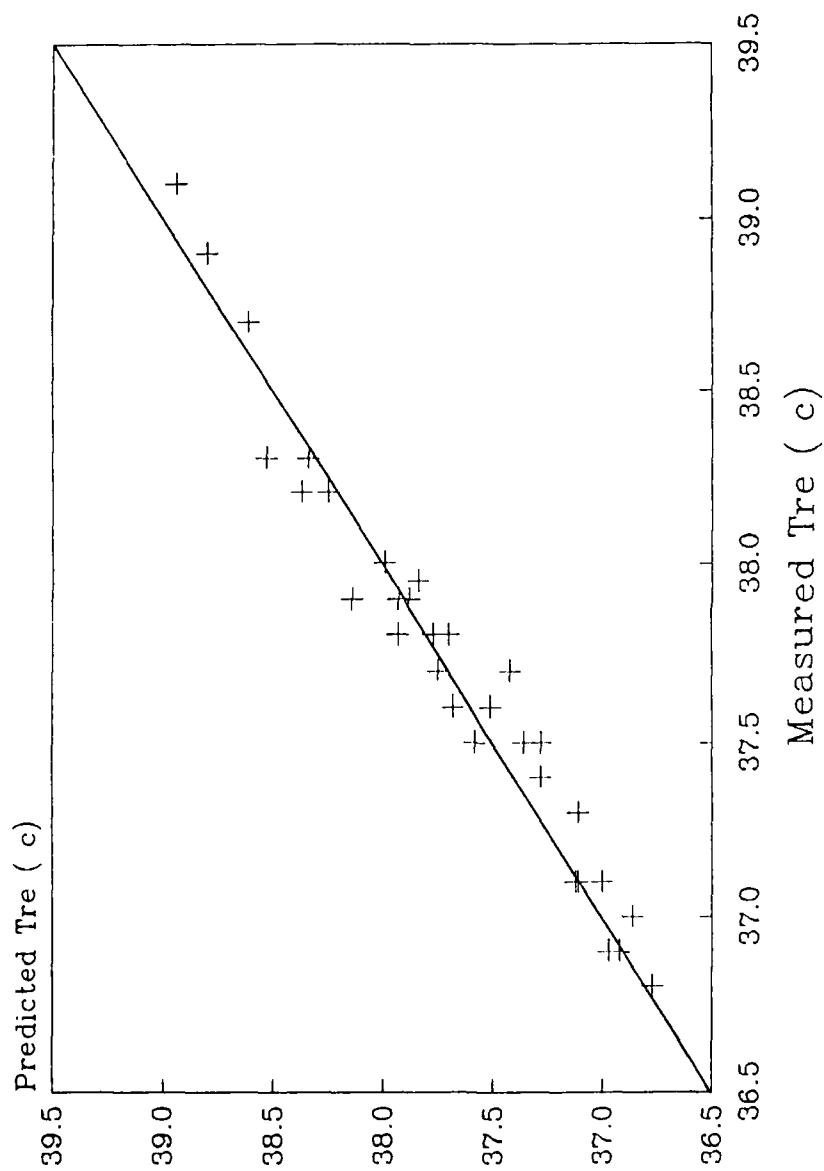


Fig. 19

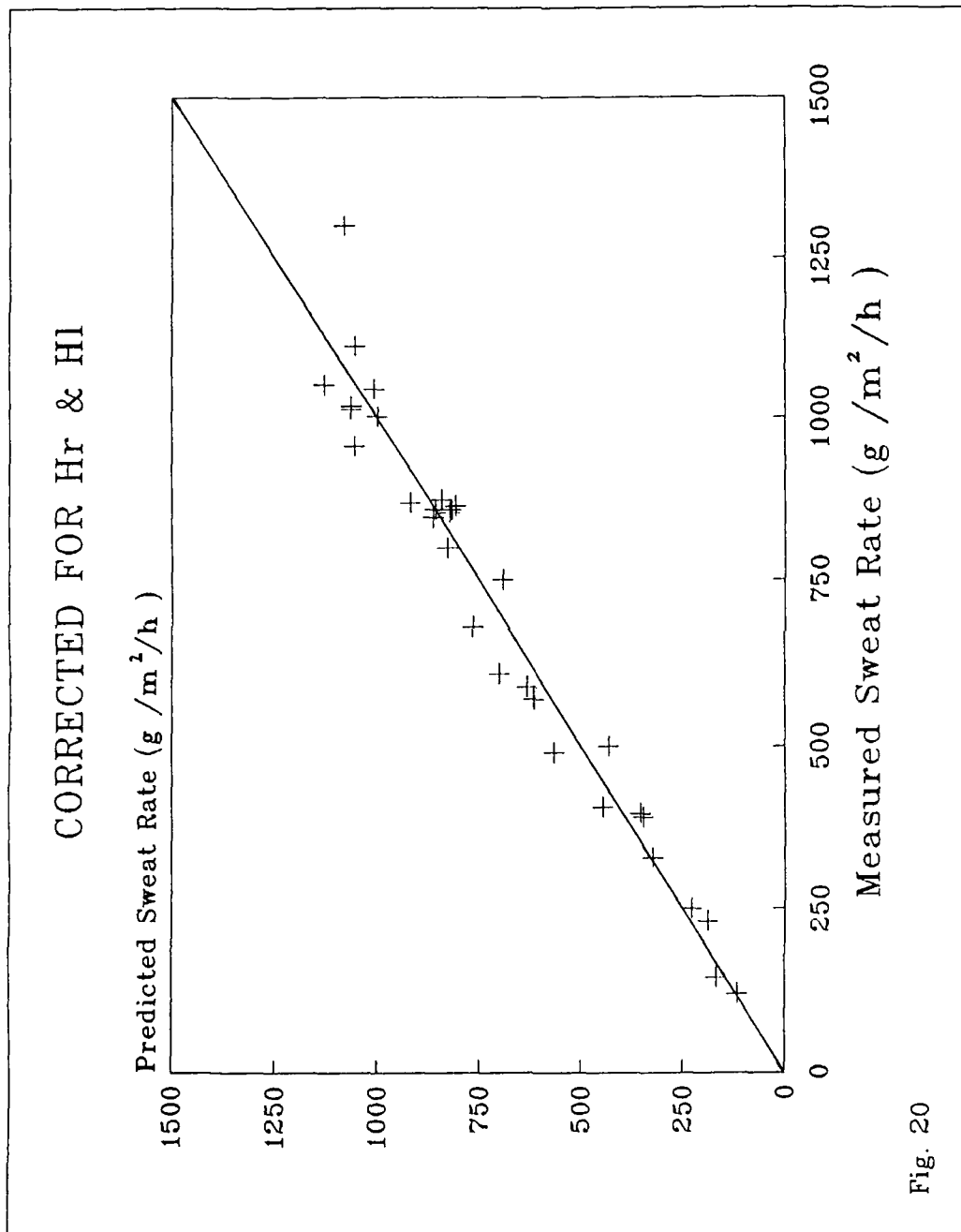


Fig. 20

### Appendix 1

During the study solar radiation was constantly measured by a pyranometer (EPLAB radiometer). In an attempt to use simple terms in the prediction models the mean radiant temperature (MRT) was used, as suggested by Bedford (1) and modified by USARIEM as follows:

$$\Delta \text{MRT} = (1 + 2.2 V_a^{0.5}) (T_g - T_a) ; (^\circ\text{C})$$

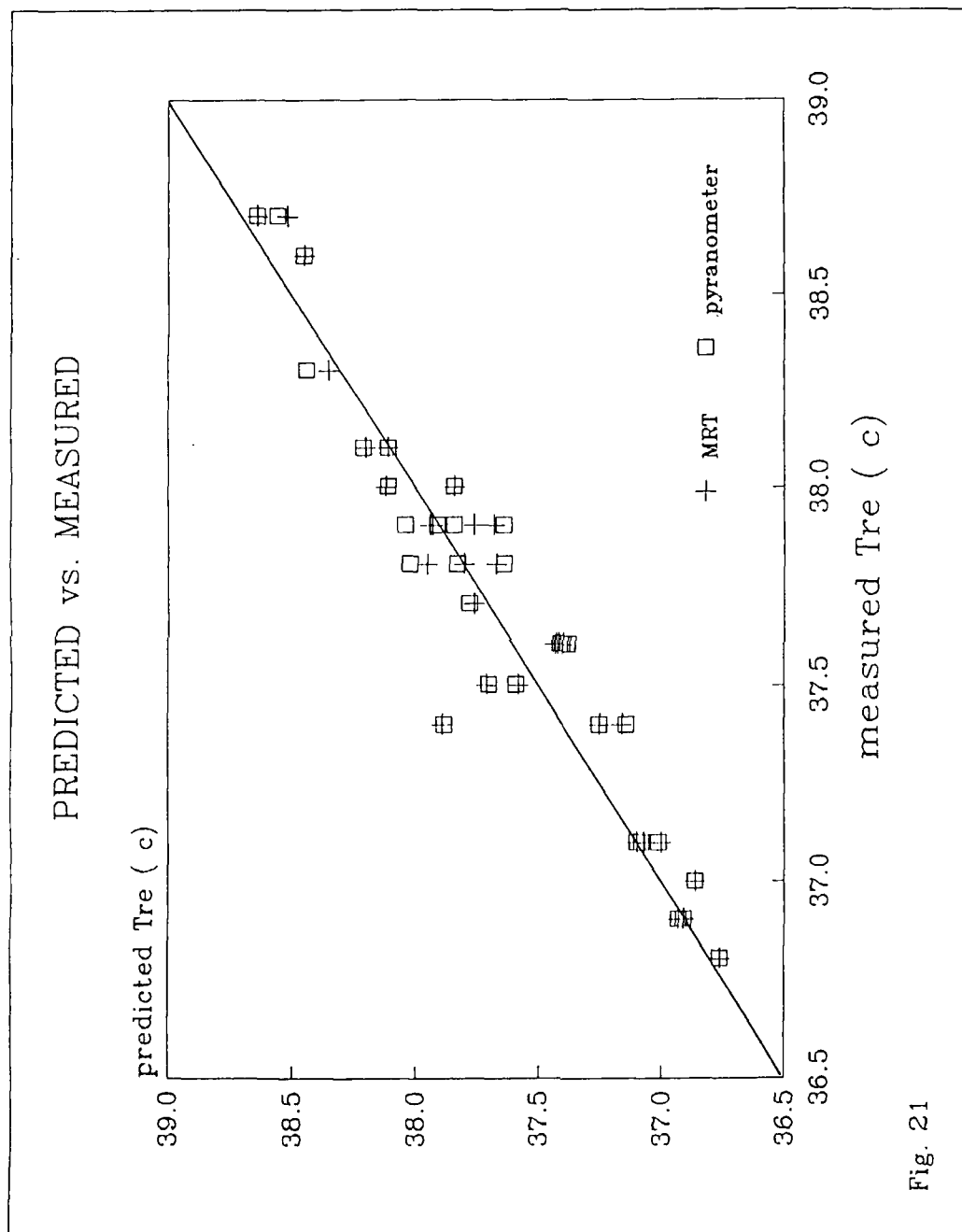
MRT was correlated with the actual measurements of solar radiation. The conversion factor between MRT and solar radiation was found to be:

$$\Delta \text{MRT} = \text{SL}^{0.6} ; (^\circ\text{C})$$

where:

$$\text{SL} = \text{solar load} ; \text{W} \cdot \text{m}^{-2}$$

Applying  $\Delta \text{MRT}$  in the prediction models revealed a high correlation between the two, both in the calculation of  $T_{re}$  (Fig 21) and in the calculation of  $m_{sw}$  (Fig 22).



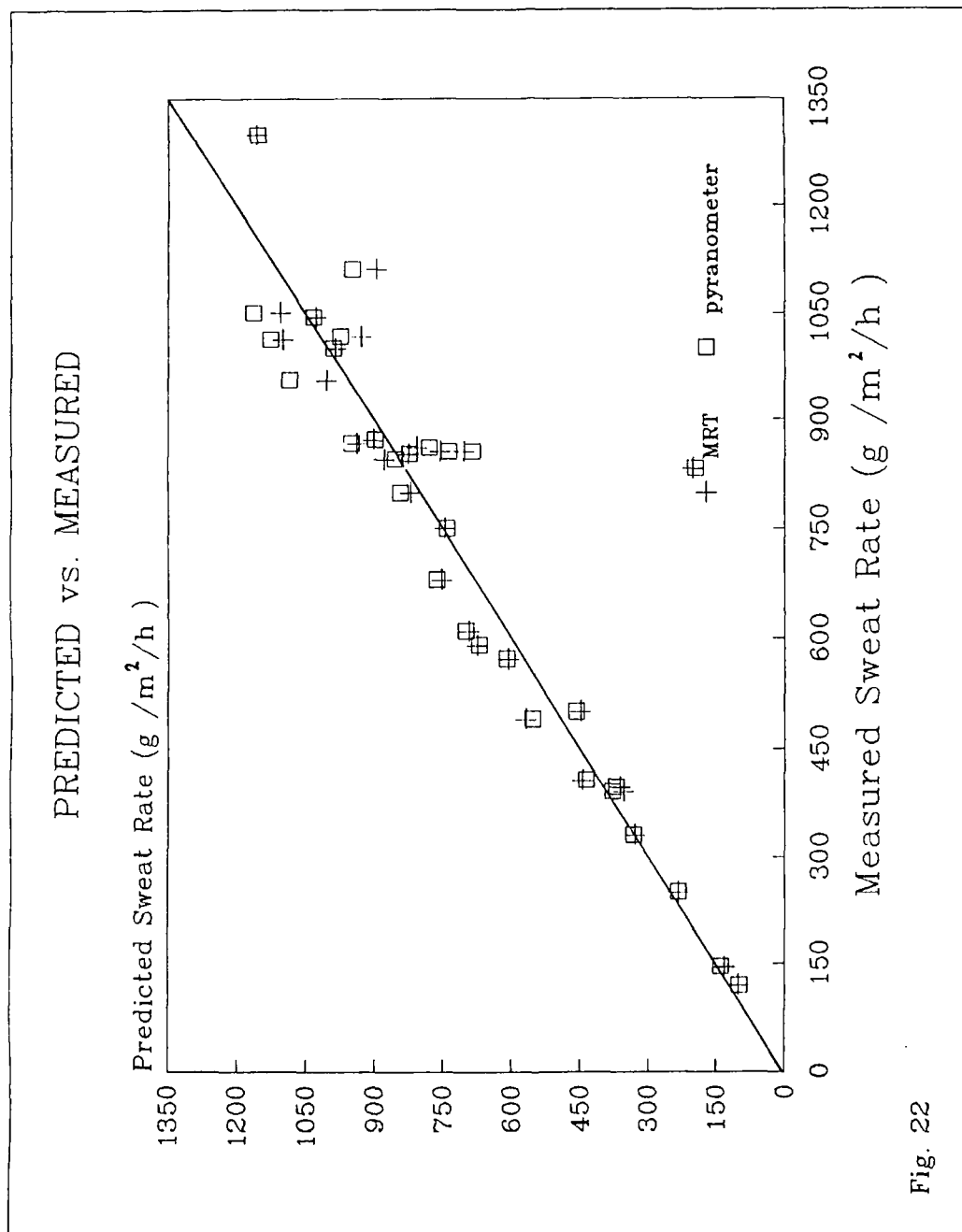


Fig. 22